1 Introduction

1.1 World's Energy Consumption

By using fossil fuels such as wood, coal, oil and gas, it was possible for humanity to set up civilization in colder climates. Due to the increasing demands of comfort, a higher mobility and a larger world population, energy consumption rose tremendously over the last 150 years (see Figure 1.1) and exhaustion of these fuels is foreseeable in the midterm.

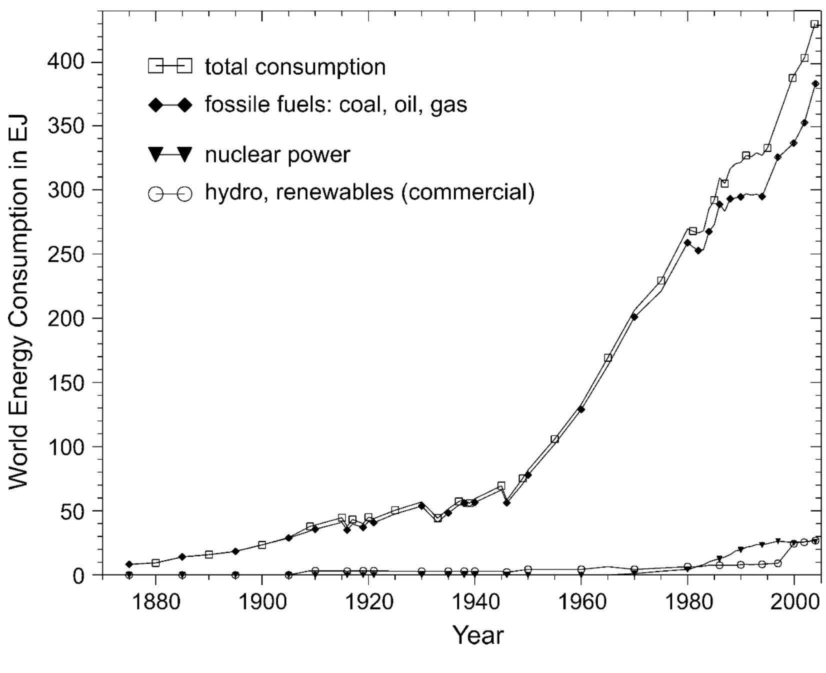

Fig. 1.1. Primary energy consumption of the world in EJ (10^{18} Joule) as a function of time (1875-1995) with shares of CO_2-emitting and CO_2-free fuels (Sources: 1875-1965: Interatom-Shell-Study 1992, 1970-1988: UN Yearbook of World Energy Statistics, 1989-2004: BP Statistic Review of World Energy, 1996)

Additionally, the emitted carbon dioxide hinders the heat radiation exchange between the Earth's surface and space, which causes climatic changing effects (see following chapters). While these facts have been known since the early seventies (Meadows et al. 1972), energy consumption of humanity (and related CO_2-emissions) rose to 429.4 EJ ($429.4 \cdot 10^{18}$ J) in the year 2004.

Figure 1.2 illustrates the potential of solar energy: the Sun's irradiation on Earth is 14,000 times higher than the World's energy consumption. Accumulated over one year, the energy of solar irradiance on Earth is much higher than all known fossil fuel resources.

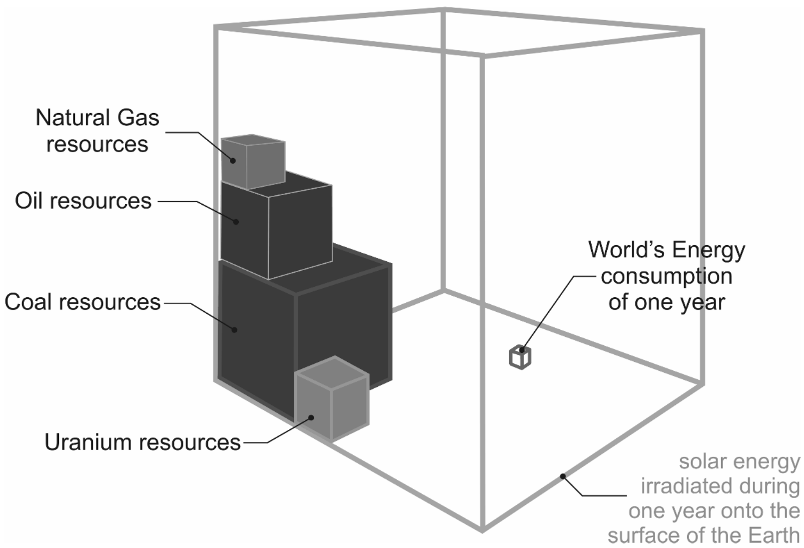

Fig. 1.2. World's energy consumption in comparison to all its fossil resources and its annual solar energy potential (adapted from Greenpeace).

1.2 CO_2-Emissions by Humankind

Human energy needs have been fulfilled by burning such fossil fuels as coal, oil and gas, which accordingly have led to elevated CO_2-emissions, especially since the beginning of industrialization as shown in Figure 1.3. Conversion back from CO_2 to O_2 by photosynthesis cannot be done entirely by the amount of plants (biomass) presently existing; thus an accumulation of CO_2 in the atmosphere is observed (see Figure 1.4). This effect is enhanced by a reduction of the amount of plants (e.g., due to deforestation).

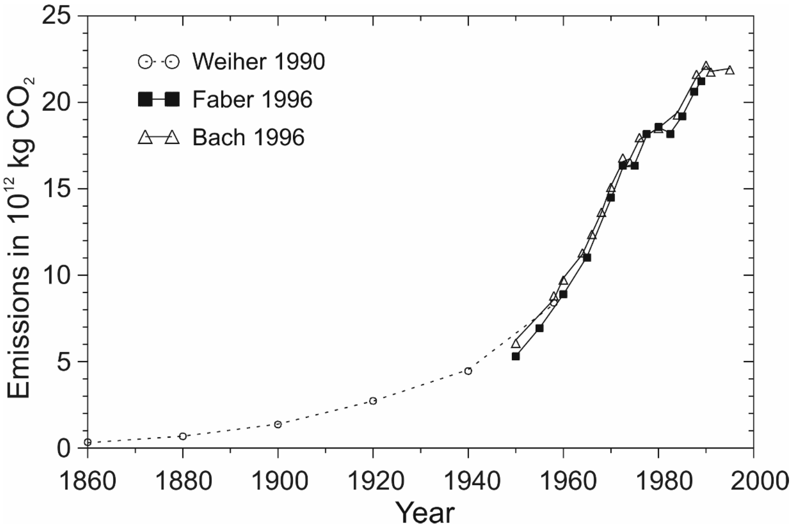

Fig. 1.3. Global anthropogenous CO_2-emissions as a function of time (1860-1995) according to Weiher 1990, Faber 1996, Bach 1996, Worldwatch 2000.

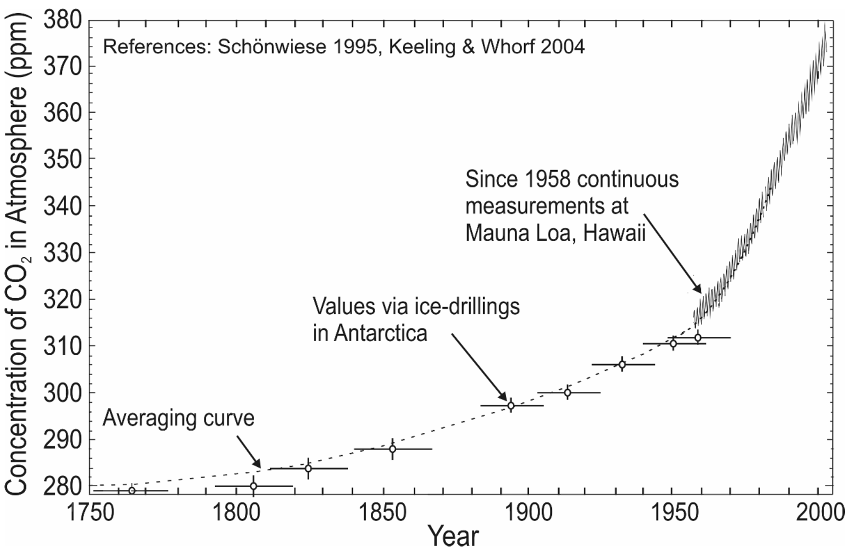

Fig. 1.4. CO_2-contents of the Earth's atmosphere in ppm ("parts per million") as a function of time. Before 1958 detection by drillings in the Antarctica: range of confidence indicated; from 1958 onwards continuous measurements at Mauna Loa (Hawaii). Graphics based on Schönwiese1995, Keeling & Whorf 2004.

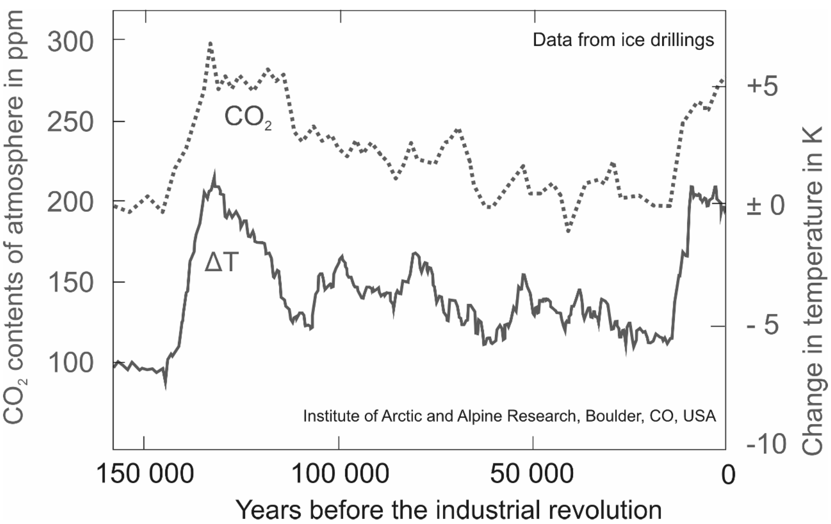

Fig. 1.5. Correlation of CO_2-contents of the Earth's atmosphere and its temperature change from 150,000 B.C to 1750 A.D. according to the Institute of Alpine and Alpine Research, Bolder, Colorado, USA, published in National Geographics 2000

1.3 Global Warming by CO_2

While the main components of the atmosphere (N_2 and O_2) allow the same good optical transmittance of incoming solar irradiation as for the heat radiation from the Earth's surface to space, the gases relevant for the greenhouse effect (such as water-vapor, methane, N_2O, and ozone) show a good transmittance just for the visible part of the radiation (λ = 350–800 nm), but hinder the emission of infrared heat radiation (λ > 10,000 nm) from earth to space. An equilibrium of incoming and outgoing energy flows then occurs when the earth surface is radiating more, but this occurs at a higher surface temperature - the greenhouse effect. Without this natural greenhouse effect, the surface of the earth would be about 30 K colder. An overview of the possible effects of natural greenhouse gases is given in Table 1.1.

Table 1.1. Components of natural greenhouse effect (Schönwiese 1995)

Gas, chemical formula	Share of natural increase of temperature	Relative share
Water vapor, H_2O	20.6 K	62%
Carbon dioxide, CO_2	7.2 K	22%
Ozone near ground, O_3	2.4 K	7%
Nitrous oxide, N_2O	1.4 K	4%
Methane, CH_4	0.8 K	3%
Others	ca. 0.6 K	2%
Sums of shares	33 K [1)]	100%

[1)] Alternative estimations are showing a total effect of 15–20 K only; investigations of the Intergovernmental Panel on Climate Change (IPCC 1994) are showing an effect of 30 K (incl. clouds).

Human activity has caused an increase in the emissions of natural and synthetic greenhouse gases, notably since the beginning of the industrial age. As a result, greater amounts of infrared heat radiation are trapped in the atmosphere which then causes an increase of ground surface temperature. The atmosphere's reflection of infrared radiation emitted from earth has increased by about 1% since 1850 (or by 3 W/m² over the natural back-reflection of 320 W/m², see Fischedick et al. 1999).

Climate change as a result of an elevated contents of carbon dioxide in the atmosphere had already been postulated in 1896 by the Swedish chemist Svante Arrhenius (see Arrhenius 1896). Astonishingly he predicted the dimension of the greenhouse effect by 5 K at a doubling of the CO_2-contents quite accurately. Interest in climatic research was aroused in 1938 when the British chemist Callendar showed an increase of the atmospheric carbon dioxide during the past decades. Nevertheless, an international focus on carbon dioxide only started in 1971–72 when it was recognized, that its effects could be as severe as general air pollution which had been at the foreground of discussion at the time.

In the year 1977, the World Meteorological Organization, an UN-Organization located in Geneva, Switzerland, called a commission of experts, who declared the need for a world climate congress. In 1970 that congress took place and triggered international research which resulted in a vast increase of knowledge about the climate – most specifically the mechanisms of climatic change and the greenhouse effect.

Recent results of emissions effect on the climate are given in Table 1.2. Evidently anthropogenous CO_2 with a total effectivity of 61% (50% according to Flohn 1989) has the largest effect on global warming, while methane at 15%, FCCHs at 11% (20% according to Flohn 1989) and ozone at 9% (10% according to Flohn 1989) contributes to a smaller extent.

Table 1.2. Concentration of greenhouse gases in the atmosphere and climatic efficiency of anthropogenous emitted trace gases (Schönwiese 1995, IPCC 2001)

Gas, chemical formula	Concentr. in ca. 1800 (in ppm)	Concentr. in 1991 and 2005 (in ppm)	Human-caused emissions (in Mt/a)	Avg. remain time (in a)	Relative molar greenhouse effectivity [1)]	Share on total effect [3)] (in %)
Carbon dioxide, CO_2	280	355 (1991) 380 (2005)	29,000	5 to 10 [4)]	1	61
Methane, CH_4	0.8	1.7	400	10	11 (23) [2)]	15
CFC, CFM, Freon	0	0.00025 to 0.00045	1	55 to 115	3,400 to 7,100 (12,000) [2)]	11
Dinitrous oxide, N_2O	0.29	0.31	ca. 10	130	270 (296) [2)]	4
Ozone at ground, O_3	unknown	0.015 to 0.05	ca. 500	0.1 to 0.25	unknown	9 [5)]

1) Relative molar greenhouse efficiency assuming a 100-years time horizon.
2) Values in brackets represent the latest results as published by IPCC 2001.
3) Contribution to anthropogenous greenhouse effect for a 100-y time horizon.
4) Anthropogenous effective time 50 to 200 years.
5) incl. all other relevant trace gases.

The climatic efficiency of the greenhouse effect can be validated by measurements of air temperature. Despite fluctuations, a distinct increase of the global air temperature at sea level by 0.5–1.0 K has occurred since the end of last century, as seen in Figure 1.6. Besides meteorological effects (winds and currents of the oceans, sea- and groundwater-level), this increase also causes changes of biological activity [1] that may result in major changes in the human habitat.

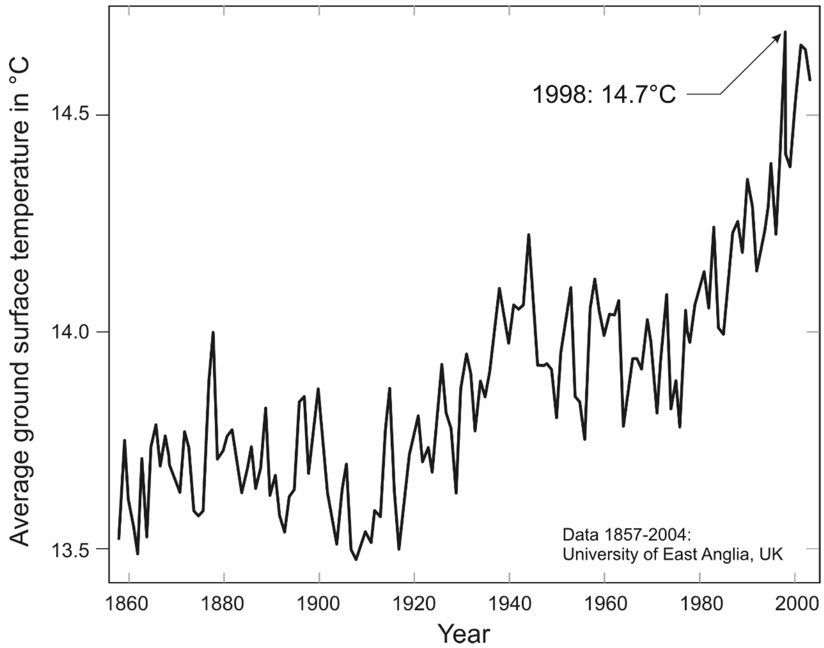

Fig. 1.6. Observed air temperature near the ground (mediated over the northern hemisphere) from 1858 to 2004.

It has also to be considered that the actual increase of temperature turns out to be lower than it should be according to the increase of atmospheric CO_2. This is due to a temporary temperature decrease caused by anthropogenous tropospheric sulfide (Newinger 1985, Charlson et al. 1992, Kiehl et al. 1993, Kaufmann et al. 1993, Charlson et al. 1994). The

[1] an increase of 10 K in temperature results in a doubling of the speed of chemical-biological reactions (RGT-rule), until an upper limiting temperature (ca. 60°C for enzymes), see Linder 1948/1977.

consequences of the increase in atmospheric temperature are not only limited to an increased frequency of natural disasters such as floods and hurricanes, see Figure 1.7, but also enhanced chemical and biological activities such as corrosion of buildings, faster growth of bacteria and the spread of disease transmitting animals. To limit such occurrences, man-made CO_2-emissions should be reduced either by a reduction in energy consumption or by adopting energies that emit less CO_2.

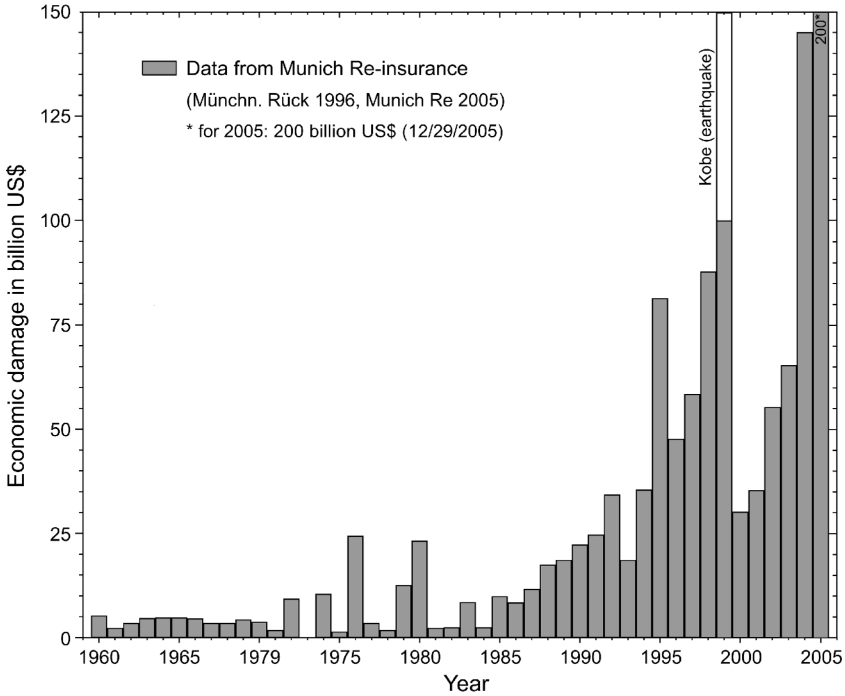

Fig. 1.7. Worldwide damage (in billions US$) caused by natural disasters as a function of time (Munich Re 2005, Berz 2003, Münchn. Rück 1996).

Yet the best solution is a combination of both strategies: energy conservation and substitution of conventional energy resources (see Fig. 1.8). Without the adoption of such policies, currently respected forecasts of anthropogenic climate change predict an increase in global mean temperatures above the pre-industrial era by 1–2.5 K by the decade of 2036 to 2046. Note, this range is relatively prone to errors in the model's climate sensibility, rates of oceanic heat uptake or global response to sulphate aerosols as long as these errors are persistent over time (Allen et al. 2000).

1.4 Measures of CO_2-Diminution

Facing the consequences of an accumulation of CO_2 in the atmosphere, the German government – as well as many other governments – decided to reduce the CO_2 emissions by 50% by the year 2020. This does not seem achievable by the means being used (i.e., merely by an increase of efficiency of power generation). While the specific crude energy demand fulfilling a certain gross national product was successfully reduced, this action alone will not meet the goal of a 50% reduction to be reached by 2020. Only if a considerable amount of energy can be generated with less emission of CO_2 can this aim be fulfilled. In a long-term perspective this means a substitution of fossil fuel power plants by renewable energy converters. Figure 1.8 shows that a reduction of CO_2 emissions becomes more effective through a combination of economic measures and replacement of CO_2 emitting power plants. According to the objectives mentioned above, future power plants have to be renewable [2]. Renewable energies are emission-free, are almost of unlimited availability, bear negligible secondary costs, their cost-trend is digressive and they have a good social acceptance by the population. In this book the use of photovoltaics for electrical energy generation is discussed; as an important example for renewable energy conversion.

[2] The use of nuclear power will not be considered as an alternative as mentioned in the treatment of the following chapter.

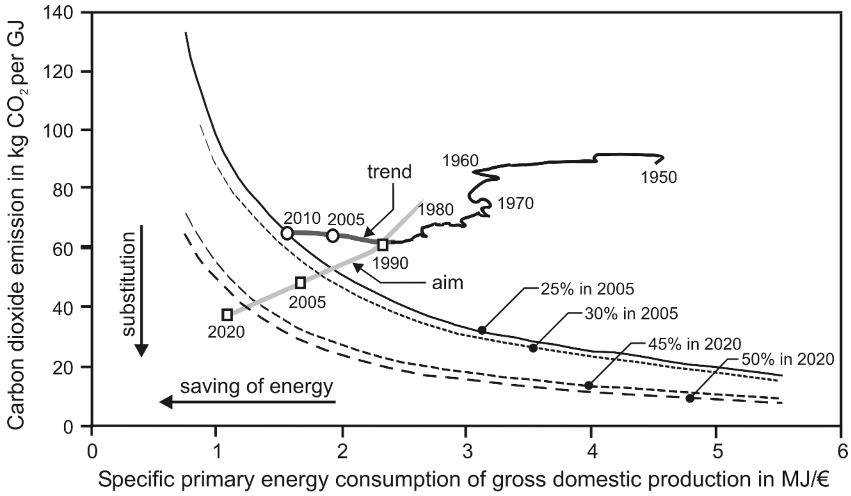

Fig. 1.8. Reduction of CO_2-emissions by depletion of energy consumption and by substitution of CO_2-intense energy generation. Also displayed are goals for CO_2 reductions.

1.5 Conventional and Renewable Sources of Energy

In the following section, the carbon based fossil sources of energy (oil, gas and coal) and nuclear power will be classed as "conventional sources of energy."

Fossil fuels are a product of the photo-synthetic process, which occurred many millions of years ago. Simply put they can be considered as none other than stores of solar energy or solar radiation. It has taken more than 100 million years to obtain the existing forms of fossil fuels and thus their formation is to be considered as a geological one-time event with extremely low conversion efficiency, see Table 1.3. From a human perspective, fossil resources must be looked upon as limited. The concept "renewable" hardly applies to them.

Table 1.3. Energy conversion time scale and conversion efficiencies of solar energy into different energy carriers

Energy carrier	Time for “production“ of energy in years	Solar conversion efficiency	Literature
Coal, lignite	> 150,000,000	< 0.001%	Bennewitz 1991
Oil, gas	> 100,000,000	< 0.001%	Bennewitz 1991
Wood	1–30	1% [3] 0.55% 0.1% [4]	Kaltschmitt 2003 Kleemann 1993 Spreng 1995
Biomass photosynthesis	0.1–1	0.3% – 5% [5] 0.04% – 1.5% 0.2% [6]	Kleemann 1993 Kaltschmitt 2003 Spreng 1995
Hydro power	0.01–1	< 1%	
Wind power	continuously	0.25% 2%	Hoagland 1996 Kleemann 1993
Photovoltaics	continuously	6% – 25%	Green 1995

The present price advantage of fossil fuels justifies itself for favorable political considerations as the price war of the oil exporting countries (OPEC), their “terms of trade” toward major countries of consumption and the direct and indirect subsidization of conventional fuels. Direct subsidization is done by giving subsidies for exploration, mining and transport: e.g., for coal and nuclear power in Germany and Diesel in Brazil. Indirect subsidization is done by charging the population and the government for the follow-up costs (e.g., air and water pollution control, security of supply for oil, security for nuclear waste). For example, measures to secure oil supply, such as military presence (e.g., in Saudi Arabia) or even

[3] i.e. beech wood: irradiance 3.7 PJ/(km^2 a), storage in dry mass above ground: 570,000 kg (240,000 kg below the ground as roots and humus).

[4] from avg. irradiance and energy density of forest growth for moderate climates.

[5] maximum of solar yield is 5.4% for sugar beets (farmland in general: 0.3%).

[6] photosynthesis related to the global average.

direct intervention (e.g., Iraque – the last war there did cost the US tax payers about 300 billion US$). Another example: Plutonium loses only 50% of its activity in 12,500 years; a 24-hrs observation by just one guard will cost 900 million US$ during that time. The price trend of conventional fuels in the medium-term fluctuated greatly (Fig. 1.9), but as a restricted commodity with constant (or even increasing) demand, its price may increase in the long term.

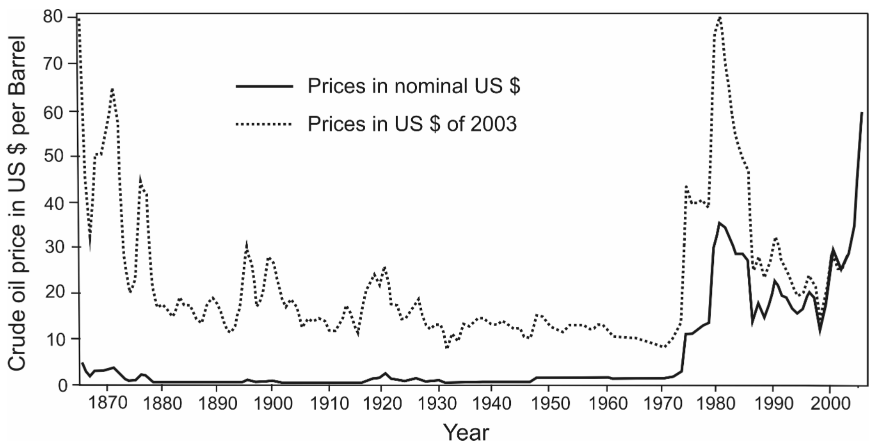

Fig. 1.9. Development in price of crude oil in US $ (actual and 2003 value) during the last 150 years.

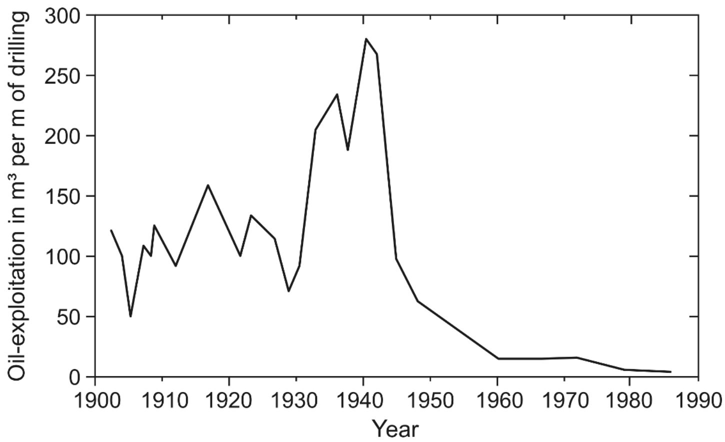

Fig. 1.10. Exploitation rate of US oil-well drillings since 1900.

An interesting aspect can be observed in the price development: in the same time period when the exploitation rate of oil drillings in the US decreased (to virtually zero) in the mid seventies (see Fig. 1.10), the oil price on the world market exploded (see Fig. 1.9), a similar (but less severe) effect could be observed in the mid forties.

Social effects caused by using these sources of energy must be considered also, such as increasing health impairments (respiratory tract illnesses, allergies etc.) and destruction of cultural possessions and environment (acid rain), too (see Hohmeyer 1989). Destruction caused by air pollutants is exemplified by the damage to historical buildings and monuments in Munich (shown in Figure 1.11): From 1700 to 1850, the time taken to increase by one grade of damage by air pollutants was calculated to be more than 300 years; this dropped suddenly to less than 50 years, in the period between 1930 and 1955. Today the time to increase one grade of damage is between 70 and 120 years, depending on the time of the building's construction. This means a doubling for the costs of restoration compared to 150 years ago, although the pollutants already have been reduced to some extent. The accumulated costs for additional restorations of cultural monuments in Germany are approx. US$ 70 billion for the year 2000. For buildings without cultural value (structures, bridges, industrial plants, high voltage transmission towers) the costs for additional maintenance due to damage by air pollutants are about US $ 4.1 billion every year in Germany, according to a study of the Federal Institute of Material Research (BAM 1990).

The use of nuclear power results in non-reversible technical and administrative (also political and social) structures, which are contradicting democratic culture[7]. A study by the University of Münster (see Ewers et al. 1991) reveals costs of US $ 2.35 trillion for a severe accident in Germany by a "Biblis" type reactor.

[7] Highly radioactive nuclear waste has half-life periods of several thousand years (e.g. Plutonium: 12,500 years) and must be reliably guarded and supervised over many such half-lifes. The consequent technical, administrative and military structure is irreversible even by public demand. Thus this complex will be immune to democratic rules.

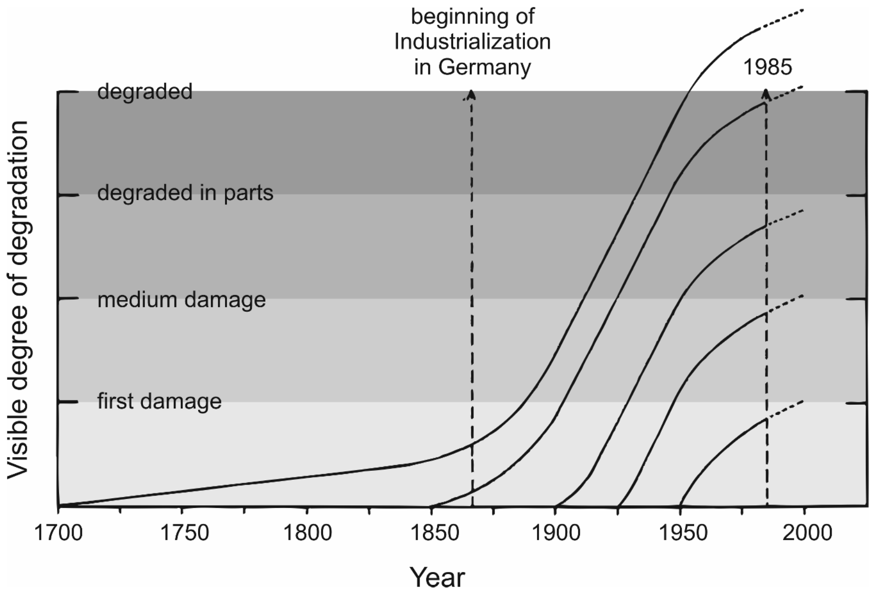

Fig. 1.11. Damage of historical buildings in Munich (Germany) as a function of time according to the *Preservation Office for Historical Monuments of the State Government of Bavaria*. Graph by Grimm et al. 1985.

The actual insurance for such an event is limited to US $ 294 million, so the costs for the insurance are underestimated by a factor of at least eight thousand. Since this form of energy use is in principle different from all other forms, and is not also momentarily ascertainable and comparable, the use of nuclear power will not be further considered at this account.

1.6 Energy Conversion

Different examinations have been already published on the energy requirement of power station facilities and the funds required for the operation with fossil and regenerative sources of energy (Aulich 1986, Schäfer 1988, Jensch 1988, Hagedorn 1989, Real 1991, Cap 1992, Spreng 1995, etc.). A short overview of the results is given in Table 1.4, see also Table A3.

Table 1.4. Emission of carbon dioxide for the conversion of fossil and renewable energy sources into electricity (in g of CO_2 per generated kWh of electricity) according to literature from 1991 to 2005.

Reference / Fuel	Faninger 1991[1)]	Stelzer et al. 1994[2)]	DB 1995	DB 1995[3)] (CO_2-equiv.)	Voß 1997	Kalt-schmitt 2003 (CO_2-equiv)	Alsema et al. 2005[4)]
Wood	940						20
Coke	960						
Briquette	910						
Lignite	890		1,135.6	1,146.6			
Coal	860	830 –840	917.7	1,049.0	878.4 –881.3	839	1,000
Fuel oil (light)	720						
Natural gas	480					399	400
Wind power		8.0 –16.3	0.7	1.1	8.1 –35.7	23 – 48	8
Hydro power		100	1.4	1.8		10–21	
Photovoltaics (PV)		230 –300	51.7	61.2	206 –318	123 –279	26 –41

1) Details of Faninger 1991 are based on details concerning values for light fuel oil or natural gas of Cap 1992.
2) Details from Stelzer et al. 1994 are partial based on studies in 1993.
3) The survey commission of the German Bundestag (ref. DB 1995) also considered the CO_2 equivalent of other climatic relevant gases. For PV, CdTe technology was considered, according to GEMIS 1992.
4) Life-cycle greenhouse gas emissions, for wood LCA of biomass is considered, for photovoltaics grid-connected PV at 1,700 kWh/(m²a) irradiation.

It is clearly visible that during the last decade the relative emissions for solar electricity via photovoltaics sank from 230–318 g/kWh to 26–41 g/kWh due to considerable improvements in the production technology and use of materials. The very latest development indicates that, triggered by a shortage in the silicon supply, a reduction of standard wafer thicknesses from 0.3 mm to 0.2 mm will take place, therefore the values of latest publication by Alsema et al. 2005 will probably be underrun by 25–30%.

While the absolute values of the specific energy requirements and greenhouse gas emissions of PV technology may change during the years, this book should still keep its value, because the accounting method presented will still be valid in the future. Further information is given in the later chapters and in the Annex.

In the past, improprieties occurred with respect to energy amortization times. Often, the required operating fuels, such as combustibles, have not been included in the considerations. A simple coal power station, for example, achieved an “energy amortization time“ of one year, in comparison to a PV power station with four years. However, utilizing the upper definition, a primitive campfire on the ground would have the best amortization time of all power stations. It is in this way that renewable energy sources have been discredited (either by purpose or by ignorance) for some time. Any energy conversion facility operated by combustible fuels has an infinite energy amortization time! Every renewable energy conversion facility works with renewable fuels, so it does not need to be counted.

Concerning the greenhouse effect, the main issue is not only energy consumption, but the effective emission of CO_2 during a complete life-cycle of a power station, its components and materials, including recycling. For example, although aluminum production has an energy consumption that is ten-times higher than stainless steel; nevertheless this may be acceptable, if this energy is generated by renewable energy sources (as it is for aluminum production in the Scandinavian countries) and the aluminum recycled later on, which allows recovery of 90% of the energy used, thus diminishing effective CO_2 emissions. (E.g., in Brazil more than 90% of the aluminum cans are recycled, see also Tables 8.1, & 8.2).

1.7 Approach

The aim of this account is to examine, how the massive use of PV generators affects the net CO_2 emission of the population. To achieve that, the complete life cycle of the PV-generator has to be considered, including factors such as production, transport, mounting, use, electrical yield and dismantling efforts.

1.7.1 Production

Besides observing the present state-of-the-art production methods, other measures that are leading to more environmentally sound production of PV-systems are examined. Here particularly the diminution of the expenditure of energy (at the same yields) and the CO_2 emissions are decisive.

1.7.2 Yield

The electrical energy generated by a photovoltaic power plant will be examined, considering all relevant parameters such as the location (irradiance, reflective losses, micro climates) and the possible interactions of these parameters.

1.7.3 Balance

The specific reduction of CO_2 through utilizing a PV system will be examined by Life Cycle Analysis (LCA). Besides being an adequate method of production (minimization of cycles of energy and matter), the system has also to increase the yields without considerable effort, if possible. New in this book is the approach by an integral analysis of a complete system, considering the origin of its components under inclusion of the recycling ability, and the operating conditions.

1.7.4 Optimization

The objective is the development of improved PV systems with consideration of the real environment and impacts on operation (irradiation, reflection, outside temperature, wind speed), and the interaction parameter of the single components with a view towards the optimization of the energetically weighted effectiveness. By setting up a prototype, the statements made will be checked. The possibilities of mass production and the resulting effect on the CO_2 balance will be examined.

Springer

http://www.springer.com/978-3-540-31345-8

Solar Electric Power Generation - Photovoltaic Energy Systems
Modeling of Optical and Thermal Performance, Electrical Yield, Energy Balance, Effect on Reduction of Greenhouse Gas Emissions
Krauter, S.C.W.
2006, XXI, 271 p., Hardcover
ISBN: 978-3-540-31345-8